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AVIATION SAFETY

Users Differ in Views of Collision Avoidance System and Cite Problems

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Resources, Community, and
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The Honorable Howard Wolpe
Chairman, Subcommittee on
Investigations and Oversight
Committee on Science, Space, and
Technology
House of Representatives

Dear Mr. Chairman:

For more than 30 years, the Federal Aviation Administration (FAA) and the aviation industry have been working to develop a system to help prevent mid-air and near mid-air collisions. In 1981, after evaluating several systems, FAA decided to develop and deploy the Traffic Alert/Collision Avoidance System (TCAS).[1] TCAS is an airborne, aircraft-to-aircraft system that scans surrounding airspace, warns of potential intruders, and recommends evasive maneuvers.

As you requested, this report discusses (1) pilots' and air traffic controllers' views on TCAS, (2) FAA's actions to address TCAS's problems, and (3) key aspects of FAA's software engineering approach for TCAS, including FAA's plans to verify and validate the system.[2]

Results in Brief

TCAS is now installed in a substantial portion of the U.S. commercial fleet, and both the Airline Pilots Association and FAA believe that the system adds a margin of safety to air travel. However, problems that have emerged prevent the system from reaching its full potential. The aviation community is nearly unanimous in recognizing that TCAS needs to be improved because it issues too many unnecessary alerts, causes excessive altitude deviations (over 1,000 feet), and causes pilots to miss landing approaches. Pilots and air traffic controllers stated that these problems reduce users' confidence in TCAS and the margin of safety that the system provides.

[1]FAA expects to have three TCAS models. TCAS I, the least costly and least technically sophisticated, recommends no collision avoidance maneuvers and is being designed for small commercial and general aviation aircraft. TCAS II and III are intended primarily for larger commercial air carriers. TCAS II recommends vertical avoidance maneuvers; TCAS III is under development and is expected to recommend both vertical and horizontal maneuvers. TCAS II is the subject of this report.

[2]Verification ensures that a product conforms to specified requirements, while validation ensures that the product completely and correctly meets users' needs.

FAA plans to reduce unnecessary alerts by modifying TCAS and will complete a series of interim computer simulation tests and a safety study to ensure that the modifications can be introduced safely in the system. FAA plans to make the modifications available at the end of March 1992. However, because FAA omitted some steps in verifying and validating TCAS before authorizing its installation in commercial aircraft, FAA still has to complete this process and plans to do so by the end of 1992.

Because FAA's planned modifications would delay TCAS alerts until intruding aircraft are closer, some members of the Separation Assurance Task Force—a TCAS review committee comprising representatives of pilots, controllers, and avionics and airframe manufacturers—believe that FAA should fully verify and validate TCAS and the modifications before implementing the modifications. However, other task force members and FAA believe that neglecting the current problems reduces pilots' confidence and presents a greater risk; therefore, according to these members, the modifications should be implemented immediately. We see no clear-cut answer to this dilemma—both points of view have merits and entail risks.

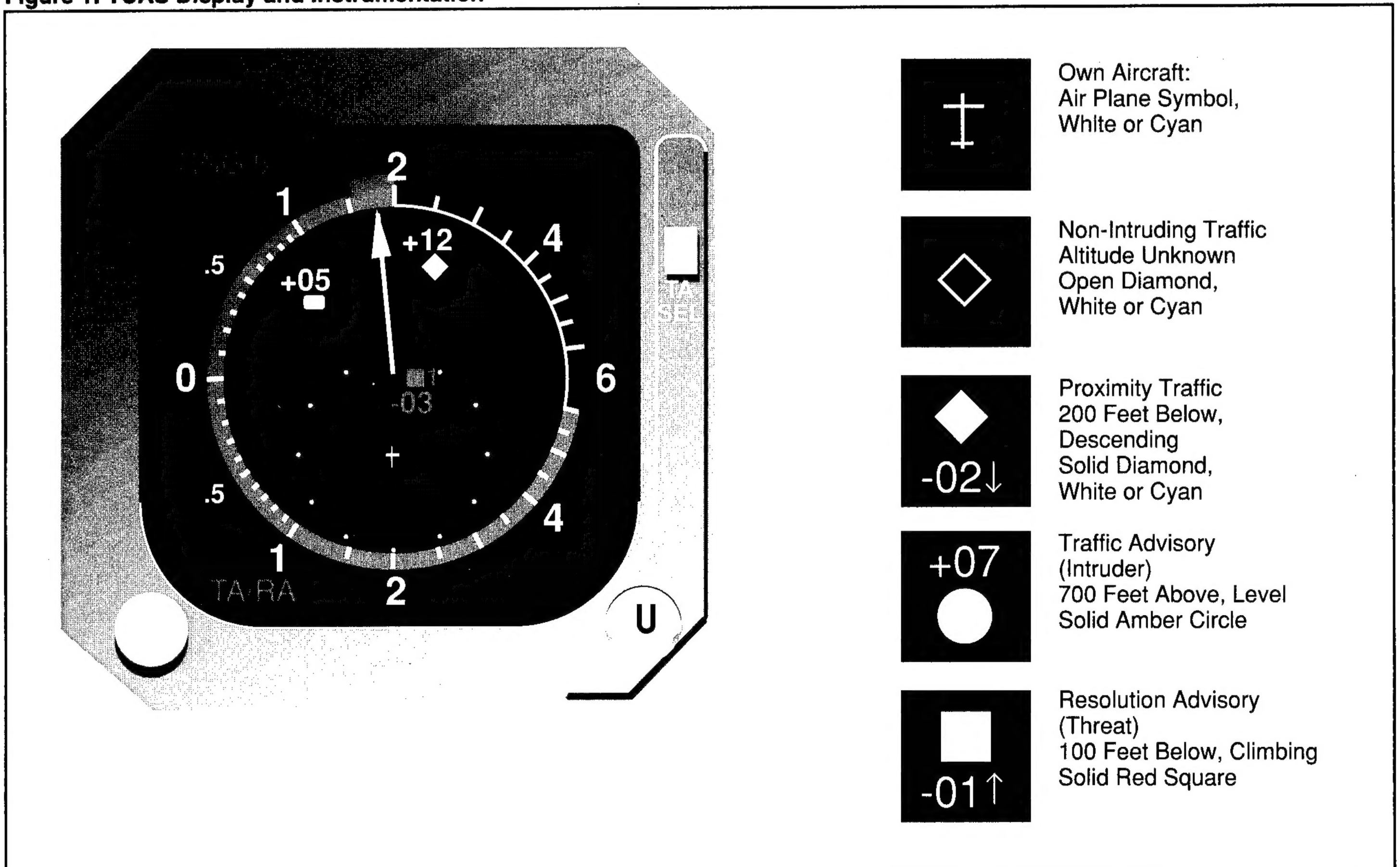
Since FAA plans to implement the modifications before completing verification and validation, we believe that, at a minimum, users should have an opportunity to review the modifications' interim test methodology and results. During the latter stages of our review, FAA decided to give the Separation Assurance Task Force an opportunity to review and comment on the test methodology and results before modifying the system. Such a step is critical to ensure that users' problems are identified and corrected and to bolster users' confidence in the safety of the modifications, even if addressing problems causes the TCAS installation schedule to slip.

Background

The Airport and Airway Safety and Capacity Expansion Act of 1987 required that all commercial aircraft with over 30 passenger seats be equipped with TCAS by December 30, 1991. A subsequent amendment gave the FAA Administrator the discretion to extend the deadline to December 30, 1993. Accordingly, FAA called for installing TCAS in 20 percent of the designated aircraft by December 30, 1990; 50 percent by December 30, 1991; and the remainder by December 30, 1993. As of December 30, 1991, 48 percent of the designated aircraft were equipped with TCAS. Airlines are continuing to install TCAS to achieve 100-percent installation by December 30, 1993, according to FAA's TCAS Program Manager.

TCAS backs up pilots' vision and air traffic controllers' monitoring systems to ensure safe separation between aircraft. TCAS's cockpit display shows surrounding air traffic, and the system verbally warns flight crews of potential and actual intrusions. Three companies—Bendix/King; Honeywell, Inc.; and Rockwell Collins—currently manufacture and market TCAS. Figure 1 shows a typical TCAS display and instrumentation.

Figure 1: TCAS Display and Instrumentation



Source: Introduction to TCAS II, U.S. Department of Transportation, Federal Aviation Administration (Mar. 1990).

Using aircraft transponder signals,[3] TCAS estimates whether one or more aircraft are likely to enter an aircraft's protected space. Initially, TCAS issues a verbal "Traffic, Traffic" warning—called a traffic advisory—if

[3]A transponder is a device that receives and transmits a radio signal for air traffic control purposes.

another aircraft comes within 1,200 feet. Flight crews use this warning and TCAS's cockpit display to see the intruder. If the intruder continues to converge, TCAS will issue a resolution advisory when the aircraft is within 400 feet at altitudes under 10,000 feet, 500 feet at altitudes between 10,001 and 20,000 feet, 640 feet at altitudes between 20,001 and 30,000 feet, and 740 feet at altitudes over 30,000 feet. The resolution advisory verbally tells the pilot to climb or descend and displays the recommended rate of climb or descent on cockpit instrumentation. The resolution advisory suggests a maneuver that is designed to maintain safe separation between transponder-equipped aircraft on the basis of TCAS's calculations of their range, altitude, and relative speed. TCAS can be operated to provide traffic advisories only, or both traffic and resolution advisories. When providing traffic advisories only, TCAS will not advise the pilot to climb or descend.

FAA and industry software engineering standards call for rigorous verification and validation throughout a system's development and testing. (App. II lists these standards.) Verification and validation are common procedures for minimizing risks on critical systems whose use could result in loss of life or some other catastrophic event. Verification and validation involve analyzing and testing software throughout its life cycle to ensure performance, integrity, reliability, safety, and quality. Although the distinction between verification and validation is sometimes blurred, we use verification to mean the steps taken to ensure that a product meets specified requirements. We use validation to mean the steps taken to ensure that the product completely and correctly meets users' needs.

Aviation Industry Has Mixed Opinions on TCAS's Benefits

The Airline Pilots Association and FAA officials agree that TCAS has increased the margin of safety in aviation travel. An Airline Pilots Association representative told us that the more experience pilots have with TCAS, the more they like it. The representative also said that pilots would revolt if TCAS were removed from the cockpit. FAA cited instances in which TCAS has helped to resolve or prevent potentially serious situations. In one instance, an aircraft equipped with TCAS was approaching a busy airport when it received a traffic advisory. When the traffic advisory changed to a resolution advisory, the crew began to climb. When clear of the potential danger, the crew leveled off and saw the intruding aircraft pass 500 feet below. This aircraft had not appeared on the controller's radar screen. In another instance, TCAS helped avoid a potential collision between a Boeing-747 and a DC-10 traveling in opposite directions in darkness over the Pacific Ocean.

The individual pilots and controllers we interviewed gave mixed reviews of TCAS. A number of pilots said they believed that TCAS is a good system or told us of incidents in which TCAS had helped them avoid other aircraft. Some pilots, however, were less complimentary, stating that TCAS interrupts normal flight procedures in the cockpit. Most of the 38 controllers whom we interviewed agreed that TCAS is a good concept but stated that problems exist. The National Air Traffic Controllers Association claims that because TCAS disrupts air traffic, the system has thus far had a negative effect on air safety. However, the association believes that as existing problems are corrected, TCAS could enhance air safety.

Pilots and Controllers Report Problems With TCAS

To evaluate TCAS's operational effectiveness and identify problems, FAA asked pilots and air traffic controllers to complete questionnaires about their experience with the system. Between June 1990 and October 1991, FAA received responses from about 2,400 pilots and 1,700 controllers. The responses identified three major concerns: (1) TCAS has issued some resolution advisories that have caused pilots to unnecessarily leave assigned airport approaches, go around airports, and reenter landing patterns (30 instances), (2) pilots have made large altitude deviations (over 1,000 feet) in response to TCAS (86 instances), and (3) TCAS has issued unnecessary advisories while pilots were following established air traffic control procedures (359 instances).

Controllers' responses indicate a major concern about TCAS's impact on their operations. Controllers stated that the altitude deviations can cause an aircraft to deviate into another sector, requiring rapid coordination between controllers, which increases their workload—a situation that controllers believe is unacceptable when air traffic is heavy. Controllers also claimed that the alerts increase communication between pilots and controllers when pilots ask about the alerts, which places additional stress on controllers, especially during high traffic periods. A National Air Traffic Controllers Association representative stated that the unnecessary alerts diminish pilots' and controllers' confidence in the system.

The National Air Traffic Controllers Association and FAA's Associate Administrator for Air Traffic also stated that excessive altitude deviations and pilots' responses to unnecessary alerts disrupt traffic and contribute to delays. The Association believes that TCAS was deployed too early, and most controllers whom we interviewed do not believe that FAA tested TCAS sufficiently to determine its impact on air traffic control operations. Both

groups believe that pilots should use only the traffic advisory feature until the problems are resolved. Such action, the Association says, would eliminate the resolution advisories that cause pilots to move out of assigned flight paths.

An FAA contractor's analysis of the questionnaire responses pointed out some factors that contribute to the excessive altitude deviations. Some pilots mistakenly believe that a "climb" or "descend" resolution advisory requires movement to the next legal altitude level, which is 1,000 feet above or below their assigned level. Pilots may also not recognize or respond appropriately to TCAS's indication that they are clear of another aircraft and may therefore continue their climb or descent unnecessarily. These issues point to training concerns that FAA and airline publications have repeatedly addressed. In addition, some reported deviations were found to be exaggerated. FAA's contractor analyzed 23 reported altitude deviations in excess of 1,000 feet and found that only 5 were actually over 1,000 feet.

Pilots' responses typically addressed TCAS's annoying repeated verbal alerts against the same known threat and indicated that the unnecessary alerts reduce their confidence in the system. FAA also believes that these problems are causing some pilots to lose confidence in TCAS and to either ignore or turn off the system during final approach. Such actions, FAA says, eliminate the margin of safety that TCAS provides. The problems that pilots cited in the questionnaire responses were also mentioned by many of the pilots whom we interviewed. Some also said that they turn the system off to avoid unnecessary alerts.

Two reasons have been cited for the unnecessary advisories. First, TCAS can sound a traffic advisory when vertical separation between aircraft is projected to be less than 1,200 feet, whereas standard air traffic control procedures allow separations of as little as 500 feet. Second, air traffic control at some airports directs aircraft to take off and climb to altitudes below other aircraft. In such instances, the aircraft remain separated in accordance with normal standards. However, because TCAS computes potential conflicts on the basis of an intruding aircraft's trajectory and rate of speed, the system cannot anticipate that the climbing aircraft will level off. Therefore, TCAS issues a resolution advisory.

An Important Element of TCAS's Software Was Not Fully Validated

Validation involves users' reviewing a system's initial specifications to ensure that the system will meet users' needs when it is built. The validation process includes a formal review of a system's initial specifications and a formal, documented resolution of users' concerns to ensure that the system will meet users' needs. Verification involves testing the system to ensure that it performs according to its specifications.

Software engineering standards in place when TCAS's specifications were being developed recognized the importance of verification and validation in developing critical software-intensive systems.[4] Because verification and validation occur throughout development, they can identify problems at any time. However, these processes are designed to identify problems early, when they are easier and less costly to fix.

Before installing TCAS in commercial aircraft, FAA verified that TCAS performed in accordance with its specifications by conducting thousands of simulated air traffic scenarios and about 6,200 hours of flight tests from 1982 to 1989. These tests confirmed that TCAS performed according to its specifications. However, FAA did not validate a key element of TCAS—the collision avoidance requirements. According to a TCAS manufacturer, no system-level specifications were developed for this portion of the system. System-level specifications facilitate validation because they are written in terms that users can easily understand.

Rather than developing system-level specifications, FAA and the aviation industry defined the collision avoidance requirements in pseudocode, a detailed specification language similar to a high-level programming language. FAA believed that pseudocode was necessary to help ensure that each of the three TCAS manufacturers' systems coordinated collision avoidance maneuvers correctly with the other manufacturers' systems. Pseudocode helped ensure coordination among three manufacturers' versions because it defined the collision avoidance specifications precisely and unambiguously, thereby providing the manufacturers with little leeway in interpreting the specifications. This precision, in turn, ensured that the manufacturers would interpret the specifications correctly and consistently.

Pseudocode also allowed FAA to verify that TCAS met its specifications. From this perspective, FAA's software engineering approach was judicious

[4]Software Considerations in Airborne Systems and Equipment Certification, Radio Technical Commission for Aeronautics (RTCA/DO-178, Nov. 1981) and Guideline for Lifecycle Validation, Verification, and Testing of Computer Software, Federal Information Processing Standard 101 (June 1983).

and effective. However, the absence of system-level specifications for TCAS's collision avoidance requirements limited the opportunities for users to participate in tests for ensuring that the system would meet their needs. FAA has since recognized the need to develop system-level specifications and perform full verification and validation of TCAS and is taking steps to complete both by the end of 1992.

Unnecessary Alerts Were Identified Late in the Process and Not Effectively Resolved

Although validating TCAS's collision avoidance requirements might have identified the unnecessary alerts early in TCAS's development, the problem emerged later as FAA verified TCAS during flight testing. In this regard, FAA's testing program was effective. However, FAA did not adequately resolve the problem once it surfaced. Specifically, after users pointed out TCAS's unnecessary alerts, FAA and the aviation industry chose not to conduct further testing to evaluate the significance of the problem because of a congressional mandate to install TCAS in the entire aircraft fleet by December 30, 1991. At that time, legislation extending the installation deadline to December 30, 1993, had not been passed. FAA's TCAS Program Manager believes that although the test results adequately ensured TCAS's safety, further testing might have allowed FAA to better assess the significance of the problem. In view of the legislative deadline, FAA and industry representatives decided to implement a procedural "work-around" that gave pilots the option to operate TCAS in the traffic advisory mode only during final approach and in certain other circumstances.

This action did not solve the problem because some airlines required pilots to operate TCAS in the resolution advisory mode throughout flight. In addition, when in the traffic advisory mode, TCAS still issues the repeated verbal alerts against other aircraft while routine separation is being maintained. Hence, the unnecessary alerts and deviations continue to be a major source of discontent among pilots and controllers. To address these problems, FAA will modify TCAS's specifications by the end of March 1992.

FAA's Plan to Modify TCAS Generates Controversy

Opinion within the aviation industry is sharply divided on whether FAA should introduce the modifications to TCAS before completing full verification and validation. FAA plans to provide modified specifications to TCAS manufacturers in March 1992 but will not complete verification and validation until the end of 1992. FAA expects the modifications to reduce the length of time and distance at which TCAS sounds alerts, bringing TCAS's parameters more in line with air traffic control separation standards.

Below altitudes of 5,000 feet, warning time for pilots would be reduced by 20 to 25 percent. For example, at an altitude of 1,500 feet, TCAS currently provides a resolution advisory 20 seconds before an aircraft is projected to approach within 400 feet, whereas under the modifications the warning would occur only 15 seconds before the projected approach. According to FAA and TCAS manufacturers, these modifications do not require significant software changes and no new functions are being introduced.

FAA and Some Industry Members Believe Modifications Should Not Be Delayed

FAA officials believe that the modifications should not be delayed until FAA has fully verified and validated TCAS (i.e., completed all verification and validation steps previously omitted). They believe that deferring the modifications would further erode pilots' confidence in TCAS and increase the number of pilots ignoring or turning off the system. FAA's TCAS Program Manager believes that a similar loss of confidence by pilots in another avionics system, the ground proximity warning system, resulted in a 1978 crash at Pensacola, Florida. According to a National Transportation Safety Board report, the flight engineer's turning off the ground proximity warning system contributed to the accident.

FAA officials stated that ongoing computer simulations and a safety study, which will be completed before the modifications are made available to TCAS manufacturers, will demonstrate that the modifications will not adversely affect safety and that modified and unmodified systems will interact properly. Therefore, FAA believes that the changes can be introduced safely before TCAS has been fully verified and validated.

One of the three TCAS manufacturers plans to proceed with the modifications in the belief that FAA's testing will have been adequate to demonstrate their safety. The National Air Traffic Controllers Association also sides with FAA because it wants to see an end to unnecessary traffic disruptions caused by TCAS alerts.

Some Industry Members Believe Modifications Should Be Delayed

Some members of the Separation Assurance Task Force—a TCAS review committee comprising representatives of pilots, controllers, TCAS engineers and manufacturers, airlines, and a major airframe manufacturer—believe that reducing aircraft separation and warning time for pilots will create an unacceptable risk. They believe that implementing the modified TCAS should be deferred until TCAS has been fully verified and validated in accordance with widely accepted software engineering practices. They also noted that the planned modifications involve changes

to the software that may introduce new problems in other parts of the system. They said that until TCAS has been fully verified and validated, they could tolerate the existing distractions rather than expose themselves to new risks.

Other members of the aviation industry expressed similar views. Representatives of the Boeing Commercial Airplane Group told us that they are opposed to modifying TCAS before it has been fully verified and validated. Representatives from two TCAS manufacturers said that they do not plan to adopt the modifications because the airlines they service do not believe that the false alerts are serious enough to warrant the increased risks inherent in reduced aircraft separation and reduced warning time for pilots. Because these two manufacturers do not plan to incorporate the modifications, some Separation Assurance Task Force members expressed concern that collision avoidance coordination problems may arise between modified and unmodified systems.

During the latter stages of our review, FAA decided to give the task force an opportunity to comment on and question the test methodology and results before providing the modifications to TCAS manufacturers. If the process raises significant concerns, the modifications will be delayed until the problems have been resolved. FAA believes that this step is necessary to enhance users' acceptance of the modifications. FAA had initially planned to brief the task force after providing the modifications to TCAS manufacturers.

Conclusions

Because TCAS directly affects air safety, those associated with the system hold strong opinions concerning its benefits. Most members of the aviation industry share the opinion that the concept is good but differ in their views on the significance of the problems reported in implementing TCAS. Operational experience to date has shown that human factors—pilots' confidence in TCAS and controllers' acceptance of the system—are important to its success. We believe that FAA should have fully verified and validated TCAS before authorizing its installation in commercial aircraft, and we endorse FAA's plans to complete the full verification and validation process at the earliest possible date.

A number of TCAS users are skeptical that the planned modifications can be introduced safely before full verification and validation have been completed. FAA's plans to allow the Separation Assurance Task Force to comment on the testing methodology and results before FAA provides the

modifications to TCAS manufacturers should help alleviate this skepticism and strengthen users' confidence in the safety and effectiveness of the modifications. Although responding to issues that may arise during this review could delay FAA's scheduled release of the modifications in March 1992, we believe that adequate attention to users' concerns is essential to gaining the aviation community's acceptance of the modifications.

As TCAS is installed in the remainder of the fleet, other system difficulties affecting safety could emerge, just as the unnecessary alerts occurred during testing. FAA tried to address that problem in a manner that allowed it to meet a legislative deadline for installing TCAS. Because the solution was not entirely effective, FAA is now faced with modifying systems already installed in approximately half the commercial fleet. If similar operational difficulties occur in the future, FAA's recent experience may suggest the advisability of delaying further installation or possibly rendering existing units inoperative until the problems have been resolved. Although such actions could require FAA to seek an extension of the December 30, 1993, deadline for installing TCAS in all aircraft, such a trade-off in the name of safety would appear prudent.

Recommendation

We recommend that the Secretary of Transportation direct the FAA Administrator to follow through on current plans to (1) fully verify and validate all future significant modifications of TCAS, (2) effectively involve TCAS users and other interested parties in testing modifications through commenting on and questioning the test methodology and results, and (3) address all users' concerns.

Agency Comments

We discussed the facts presented in this report with FAA officials, who generally agreed with the facts but disagreed with our statements concerning users' lack of involvement in TCAS's initial design. In response to FAA's concerns, we gathered additional data and incorporated the results. As requested, we did not obtain written agency comments on a draft of this report.

We conducted our review from July 1991 to January 1992 in accordance with generally accepted government auditing standards. A detailed discussion of our objectives, scope, and methodology appears in appendix I.

Unless you publicly announce its contents earlier, we plan no further distribution of this report until 30 days from the date of this letter. At that time, we will provide copies to the Secretary of Transportation; the Acting Administrator, FAA; the Director, Office of Management and Budget; and other interested parties. We will send copies to others upon request.

Our work was performed under directors in two GAO divisions. Kenneth M. Mead, Director of Transportation Issues in the Resources, Community, and Economic Development Division, can be reached at (202) 275-1000. JayEtta Z. Hecker, Director for Resources, Community, and Economic Development Information Systems in the Information Management and Technology Division, can be reached at (202) 336-6416. Other major contributors to this report are listed in appendix III.

Sincerely yours,

J. Dexter Peach
Assistant Comptroller General

Contents

Abbreviations

FAA	Federal Aviation Administration
TCAS	Traffic Alert/Collision Avoidance System

Objectives, Scope, and Methodology

The Chairman, Subcommittee on Investigations and Oversight, Committee on Science, Space, and Technology, asked us to review a number of issues related to the Traffic Alert/Collision Avoidance System (TCAS). Specifically, we were asked to develop information on (1) pilots' and air traffic controllers' views on TCAS, (2) FAA's actions to address TCAS's problems, and (3) key aspects of FAA's software engineering approach for TCAS, including FAA's plans to verify and validate the system.

To obtain information on the status of TCAS's installation and reported operational problems, we reviewed relevant sections of the Federal Aviation Act of 1958, as amended, and FAA's TCAS regulations, as well as advisory circulars and various reports and position papers that provided information on TCAS operations and issues. We reviewed statistics developed by FAA's TCAS Transition Program to determine the number of altitude deviations and inappropriate TCAS advisories reported by pilots and air traffic controllers.

We discussed TCAS's operational problems with FAA's TCAS and air traffic officials and attended biweekly meetings that FAA instituted to keep senior-level management apprised of developments in the TCAS program. We also attended meetings of various working groups, task forces, and technical committees involved with implementing TCAS to obtain perspectives from many segments of the aviation community, including pilots, air traffic controllers, TCAS manufacturers, airline officials, technical consultants, and aircraft manufacturers. To discuss reported problems, we met with representatives of the National Air Traffic Controllers Association, Airline Pilots Association and airlines, and with contractors working on various aspects of TCAS. We also visited officials at Boeing Commercial Airplane Group to obtain that company's perspective on TCAS, and we discussed TCAS's reported operational problems with representatives of each of the three TCAS manufacturers. We also interviewed 38 air traffic controllers and 70 pilots. Because we judgmentally selected these individuals, our findings cannot be generalized to the universe of pilots and air traffic controllers. In addition, to observe TCAS in operation, we rode in the cockpit "jump seat" on 10 Simmons Airlines, Inc./American Eagle commuter flights into and out of O'Hare Airport, as well as 4 USAir Express flights into and out of Washington National Airport.

To obtain information on TCAS software development and testing, we met with FAA and contractor officials involved in the development and testing of TCAS. We also talked to avionics manufacturers currently producing TCAS

units. We reviewed TCAS requirements documentation, test plans, safety studies, test reports, certification standards, and verification and validation plans. We interviewed (1) FAA officials at the TCAS program office and aircraft certification offices in Washington, D.C., and at the FAA Technical Center in Atlantic City, New Jersey, and (2) software development experts at the Mitre Corporation in McLean, Virginia, and at the Massachusetts Institute of Technology's Lincoln Laboratory in Cambridge, Massachusetts.

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